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A Gauge-Mediation Model with a Light Gravitino of Mass O(10) eV and the Messenger Dark Matter

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Abstract

In the light of recent experimental data on gaugino searches, we revisit the direct-transmission model of dynamical supersymmery breaking with the gravitino mass $m_{\tilde{G}} \leq 16$ eV, which does not have any cosmological or astrophysical problems. We find that in the consistent regions of parameter space, the model predicts not only upper bounds on superparticle masses (1.1 TeV, 320 GeV, 160 GeV, 5 TeV, 1.5 TeV and 700 GeV for gluino, Wino, Bino, squarks, left-handed sleptons and right-handed sleptons, respectively), but also a mass of the lightest messenger particle in the range of $10 - 50$ TeV. The lightest messenger particle can naturally be a messenger sneutrino. Therefore, this may suggest that the messenger sneutrino could be the dark matter, as proposed recently by Hooper and March-Russel to account for the gamma-ray spectrum from the galactic center observed by HESS experiment.

A light gravitino of mass ≤ 16 eV is very interesting, since it does not cause any cosmological or astrophysical problems [1]. In particular, we have no so-called gravitino problem [2, 3], since the next lightest supersymmery (SUSY) particle decays sufficiently before the Big Bang nucleosynthesis. Thus, the reheating temperature after inflation can be higher than 10^{10} GeV, which is the lowest temperature for the thermal leptogenesis to work [4, 5]. However, it is very difficult to construct a consistent gauge-mediation model with such a light gravitino and only a quite few examples are known [6, 7, 8, 9]. In this letter, we discuss the model in Ref. [7] in the light of recent experimental data on the search for gauginos in a class of gauge-mediation models, and show that the minimal model in Ref. [7] is already excluded, but the next-to-minimal model still survives. We show that the model predicts not only upper bounds on superparticle masses (1.1 TeV, 320 GeV, 160 GeV, 5 TeV, 1.5 TeV and 700 GeV for gluino, Wino, Bino, squarks, left-handed sleptons and right-handed sleptons, respectively), but also a mass of the lightest messenger particle in the range of $10 - 50$ TeV. This may suggest that the lightest messenger particle is the dark matter proposed recently by Hooper and March-Russell [10] to account for the gamma-ray spectrum from the galactic center [11].

Let us briefly describe a model discussed in Ref. [7]. We assume a SUSY $SU(2)$ gauge theory with four doublet chiral superfields $Q^i_\alpha(\alpha = 1, 2;\ i = 1 - 4)$ and six singlet chiral superfields $Z_{ij} = -Z_{ji}$ [12, 13]. We impose, for simplicity, a flavor $SP(2)$ symmetry in the superpotential

$$W = \lambda_{ij} Q_i Q_j Z_{ij}, \tag{1}$$

and assume the $SP(2)$-invariant vacuum, $\langle Q_1 Q_2\rangle = \langle Q_3 Q_4\rangle = \Lambda^2$. Here, Λ is the dynamical scale of the strong $SU(2)$ gauge interactions. Then, the effective superpotential is given by

$$W_{eff} \simeq \lambda \Lambda^2 Z. \tag{2}$$

Here, the chiral superfield Z is a $SP(2)$ singlet combination of Z_{ij}. We see that the Z acquires a non-vanishing F term ($F_Z \simeq \lambda\Lambda^2$) and the SUSY is spontaneously broken [12, 13].

The low energy effective superpotential in the messenger sector is given as follows [7]:

$$W_{eff} \;=\; \lambda\Lambda^2 Z + \sum_{a=1}^{n} \left\{ Z(k_{d_a} d_a \bar{d}_a + k_{l_a} l_a \bar{l}_a) + m_{d_a} d_a \bar{d}'_a + m_{\bar{d}_a} d'_a \bar{d}_a + m_{l_a} l_a \bar{l}'_a + m_{\bar{l}_a} l'_a \bar{l}_a \right\}. \tag{3}$$

Here we introduce n sets of vector-like messenger quark multiplets $d_a, \bar{d}_a, d'_a$ and $\bar{d}'_a$ and lepton multiplets $l_a, \bar{l}_a, l'_a$ and $\bar{l}'_a$ $(a = 1 - n)$. We assume that the multiplets (d, l) and (d', l') transform as $\mathbf{5}$, and $(\bar{d}, \bar{l})$ and $(\bar{d}', \bar{l}')$ as $\bar{\mathbf{5}}$ under $SU(5)$, so that the gauge coupling unification remains in the models. Note that the perturbativity up to the GUT scale ($M_G = 2 \times 10^{16}$ GeV) allows only cases with $n = 1$ and 2.[1] We refer a case with $n = 1$ as the minimal model and a case with $n = 2$ as the

[1] Assuming $\alpha_3(m_Z) = 0.12$ (0.11) and $\Lambda = 2.6 \times 10^5$ GeV, we get $\alpha_3(M_G) \simeq 6$ (1.1) at one-loop level in the model with $n = 3$. Therefore, the model with $n = 3$ might be marginally allowed in some particular parameter regions, but we do not discuss it further in this paper.

next-to-minimal model. We also assume that the correction to Kahler potential for Z field induces the vacuum expectation value (vev) $\langle Z\rangle \simeq \Lambda$ [2]. Under the following condition,

$$\left|m_{\psi_a} m_{\bar{\psi}_a}\right|^2 > |k_{\psi_a}\langle F_Z\rangle|^2 \quad (\psi = d \text{ and } l), \tag{4}$$

we find the SUSY-breaking vacuum is true one with vanishing vevs of the messenger squarks and sleptons:

$$\langle F_Z\rangle \simeq \lambda\Lambda^2,\ \langle\psi_a\rangle = \langle\bar{\psi}_a\rangle = \langle\psi'_a\rangle = \langle\bar{\psi}'_a\rangle = 0 \quad (\psi = d \text{ and } l). \tag{5}$$

The mass terms of the messenger particles are represented as

$$\mathcal{L} = -\sum_{a=1}^{n}\sum_{\psi=d,l}\left[(\bar{\psi}_a, \bar{\psi}'_a)M^{(\psi_a)}\begin{pmatrix}\psi_a\\ \psi'_a\end{pmatrix} + \text{h.c.} + (\tilde{\psi}^*_a, \tilde{\psi}'^*_a, \tilde{\bar{\psi}}_a, \tilde{\bar{\psi}}'_a)\tilde{M}^{2(\psi_a)}\begin{pmatrix}\tilde{\psi}_a\\ \tilde{\psi}'_a\\ \tilde{\bar{\psi}}^*_a\\ \tilde{\bar{\psi}}'^*_a\end{pmatrix}\right], \tag{6}$$

where ψ and $\tilde{\psi}$ denote fermionic and bosonic components of the superfield ψ, respectively. The mass matrices $M^{(\psi_a)}$ and $\tilde{M}^{2(\psi_a)}$ are given by

$$M^{(\psi_a)} = \begin{pmatrix} m^{(\psi_a)} & m_{\bar{\psi}_a}\\ m_{\psi_a} & 0\end{pmatrix}, \tag{7}$$

$$\tilde{M}^{2(\psi_a)} = \begin{pmatrix} \left|m^{(\psi_a)}\right|^2 + |m_{\psi_a}|^2 & m^{(\psi_a)*}m_{\bar{\psi}_a} & F^{(\psi_a)*} & 0\\ m^{(\psi_a)}m_{\bar{\psi}^*_a} & \left|m_{\bar{\psi}_a}\right|^2 & 0 & 0\\ F^{(\psi_a)} & 0 & \left|m^{(\psi_a)}\right|^2 + \left|m_{\bar{\psi}_a}\right|^2 & m^{(\psi_a)}m^*_{\psi_a}\\ 0 & 0 & m^{(\psi_a)*}m_{\psi_a} & |m_{\psi_a}|^2\end{pmatrix}. \tag{8}$$

Here $m^{(\psi_a)} = k_{\psi_a}\langle Z\rangle$ and $F^{(\psi_a)} = k_{\psi_a}\langle F_Z\rangle$ ($\psi = d$ and l). Diagonalizing the mass matrices, we obtain masses of the messenger particles.

Once the messengers receive SUSY breaking masses, gaugino (sfermion) masses in the minimal SUSY standard model (MSSM) sector are generated by one-loop (two-loop) diagrams of the messenger particles via standard model gauge interactions. The gaugino masses are given by

$$m_{\tilde{g}_3} = \frac{\alpha_3}{2\pi}\sum_{a=1}^{n}\mathcal{F}^{(d_a)}, \tag{9}$$

[2]The mass parameters $m_{d_a}, m_{\bar{d}_a}, m_{l_a}$ and $m_{\bar{l}_a}$ can be generated dynamically as discussed in Ref. [7]. If $\langle Z\rangle = 0$, we may introduce mass terms $\sum_a(M_{d_a}d_a\bar{d}_a + M_{l_a}l_a\bar{l}_a)$ [7].

$$m_{\tilde{g}_2} = \frac{\alpha_2}{2\pi}\sum_{a=1}^{n}\mathcal{F}^{(l_a)}, \tag{10}$$

$$m_{\tilde{g}_1} = \frac{\alpha_1}{2\pi}\sum_{a=1}^{n}\left(\frac{2}{5}\mathcal{F}^{(d_a)} + \frac{3}{5}\mathcal{F}^{(l_a)}\right), \tag{11}$$

and the sfermion masses are

$$m_{\tilde{f}}^2 = \frac{1}{2}\sum_{a=1}^{n}\left[C_3^f\left(\frac{\alpha_3}{4\pi}\right)^2\mathcal{G}^{(d_a)2} + C_2^f\left(\frac{\alpha_2}{4\pi}\right)^2\mathcal{G}^{(l_a)2} + \frac{3}{5}Y^2\left(\frac{\alpha_1}{4\pi}\right)^2\left(\frac{2}{5}\mathcal{G}^{(d_a)2} + \frac{3}{5}\mathcal{G}^{(l_a)2}\right)\right], \tag{12}$$

where we have adopted the $SU(5)$ GUT normalization of the $U(1)_Y$ gauge coupling ($\alpha_1 = \frac{5}{3}\alpha_Y$), and $C_3^f = \frac{4}{3}$ and $C_2^f = \frac{3}{4}$ when $\tilde{f}$ is in the fundamental representation of $SU(3)_C$ and $SU(2)_L$ respectively, and $C_{3,2}^f = 0$ for the gauge singlets, and Y denotes the $U(1)_Y$ hypercharge ($Y = Q - T_3$). Here $\mathcal{F}^{(\psi)}$ and $\mathcal{G}^{(\psi)}$ are functions of the messenger masses and mixings, and their explicit expressions can be found in Ref. [7].

Since SUSY is broken, the gravitino gets a mass:

$$m_{\tilde{G}} = \frac{F_Z}{\sqrt{3}M_*} = 16\left(\frac{\sqrt{F_Z}}{2.6\times10^5\ \text{GeV}}\right)^2\ \text{eV}. \tag{13}$$

Here M_* is the reduced Planck mass ($M_* = 2.4\times10^{18}$ GeV). As pointed out in Ref. [1], the matter power spectrum inferred from large samples of Lyman-α forest data and the cosmic microwave background data of WMAP strongly constrain the gravitino mass. As a result, its current upper limit is 16 eV.[3] From Eq. (13), the gravitino mass limit translates into a limit on the SUSY breaking scale:

$$\sqrt{F_Z} < 2.6\times10^5\ \text{GeV} \longleftrightarrow m_{\tilde{G}} \le 16\ \text{eV}. \tag{14}$$

Note that in the model discussed here, the gravitino mass and SUSY breaking vev F_Z are related each other as shown in Eq. (13), because the SUSY breaking in the dynamical SUSY breaking sector is directly transmitted to the messenger sector. In most of gauge-mediation models in literatures [15], however, the SUSY breaking scale in the messenger sector is suppressed, compared to the original SUSY breaking scale, due to the transmission mechanism. Therefore we stress that the gravitino mass limit is quite severe in most of gauge-mediation models, and it is crucial to have the direct-transmission of dynamical SUSY breaking in order to construct the gauge-mediation models with $m_{\tilde{G}} \le 16$ eV.

[3] To evade the bound on the gravitino mass, one needs to consider a late-time entropy production, as suggested in Ref. [14].

Now we are in position to discuss the prediction of the model based on the limit in Eq. (14). Since the minimal model (the model with $n = 1$) has been excluded as we will see later, we mainly consider the next-to-minimal model (the model with $n = 2$). In Fig. 1, mass spectrum of the gauginos and sfermions in the MSSM sector are plotted as a function of $F^{(\psi)}/(m_\psi m_{\bar{\psi}})$ in the case of the next-to-minimal model.[4] Throughout our discussion, we assume $F^{(\psi_a)} \equiv F^{(\psi)}$, $m^{(\psi_a)} \equiv m^{(\psi)}$, $m_{\psi_a} \equiv m_\psi$, and $m_{\bar{\psi}_a} \equiv m_{\bar{\psi}}$ for $a = 1, 2$, and hence we suppress the index a, for simplicity. In Fig. 1, we have assumed all F-parameters[5] are equal, $F^{(l)} = F^{(d)} = F_Z = (2.6 \times 10^5 \text{ GeV})^2$, which corresponds to $m_{\tilde{G}} = 16$ eV, and all mass parameters are equal, $m^{(\psi)} = m_\psi = m_{\bar{\psi}}$ for $\psi = d,\ l$. In Fig. 2, we also show the mass spectrum of the gauginos and sfermions as a function of a parameter $m^{(\psi)}/\sqrt{m_\psi m_{\bar{\psi}}}$. Here we assume $m_\psi = m_{\bar{\psi}}$ and $F^{(\psi)}/(m_\psi m_{\bar{\psi}}) = 0.98$ as an example. We see that the gaugino masses are maximal for $m^{(\psi)}/\sqrt{m_\psi m_{\bar{\psi}}} \simeq 1$ with fixed $F^{(\psi)}/(m_\psi m_{\bar{\psi}})$. Because of the limit in Eq. (14), we find, in Fig. 1, the next-to-minimal model predicts upper limits on superparticle masses (1.1 TeV, 320 GeV, 160 GeV, 5 TeV, 1.5 TeV and 700 GeV for gluino, Wino, Bino, squarks, left-handed sleptons and right-handed sleptons, respectively).

Important experimental bounds on gaugino masses have been set by D0 and CDF experiments [17, 18].[6] They have been searching for diphoton events induced by the lightest neutralino decay into a gravitino plus a photon, subsequent to Wino pair production at Tevatron. The D0 lower limit on Wino mass is about 195 GeV [17] and currently it is the strongest bound for the models considered here. In Figs. 1 and 2, the D0 limit is also shown.

Note that in the minimal model ($n = 1$), the predicted upper limits on gaugino masses are half of those in the next-to-minimal model shown in Fig. 1, and hence the predicted Wino mass in the minimal model is smaller than about 160 GeV. Therefore, the D0 bound has excluded the minimal model. Since models with $n \geq 3$ are not allowed by the perturbativity up to the GUT scale as we have mentioned before, the next-to-minimal model is the only viable model.

The D0 bound constrains the parameter space in the next-to-minimal model. For example, the parameter $F^{(l)}/(m_l m_{\bar{l}})$ has to be larger than about 0.93 for $m^{(l)}/\sqrt{m_l m_{\bar{l}}}=1$, and $m^{(l)}/\sqrt{m_l m_{\bar{l}}}$ should be in the range of $0.5 - 2$ for $F^{(l)}/(m_l m_{\bar{l}}) = 0.98$, as shown in Figs. 1 and 2. The experimental bound on gluino mass is about 200 GeV for the next-to-minimal model, and hence a constraint on $F^{(d)}/(m_d m_{\bar{d}})$ is weaker than that of $F^{(l)}/(m_l m_{\bar{l}})$.

We find that there is an interesting consequence in the consistent region with $F^{(l)}/(m_l m_{\bar{l}}) \sim 1$ and

[4]Within a particle content of MSSM, μ-term tends to be larger than Wino mass because squarks are much heavier than the Wino, as discussed in Ref. [7]. Therefore, Higgsinos are heavier than Winos. However, the Higgs sector can be modified, as we will discuss later, and hence it will be model-dependent. Thus we will not discuss the Higgs and Higgsino sector in detail here. A more detail analysis will be given in Ref. [16].

[5]In our results, we assume the Yukawa couplings $k_{d_a} = k_{l_a} = 1$ because we expect these Yukawa couplings are of order one. One can easily estimate the change of our results when these Yukawa couplings are deviated from one.

[6]LEP experiments also have some constraints on gaugino masses for gauge-mediation models. However, in the models considered here, sleptons are so heavy that their limits do not give a significant constraint.

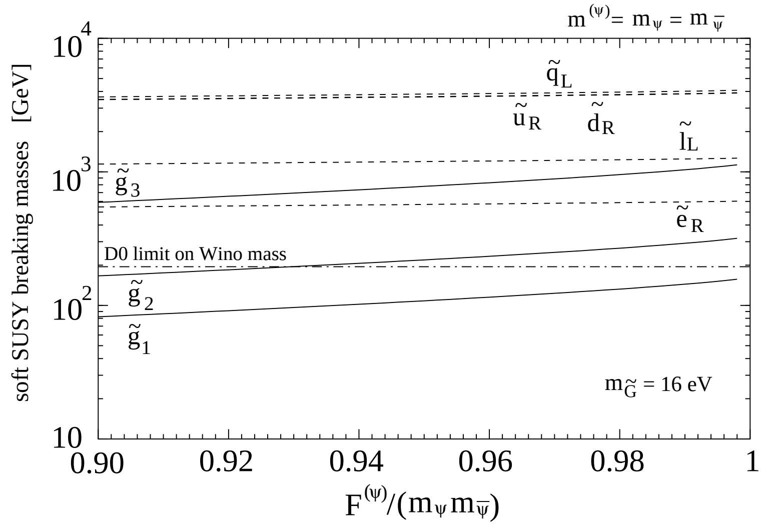

Figure 1: Mass spectrum of the gauginos (solid lines) and sfermions (dashed lines) in the MSSM sector as a function of a parameter $F^{(\psi)}/(m_\psi m_{\bar{\psi}})$ in the next-to-minimal model. Here we have assumed $m^{(\psi)} = m_{\bar{\psi}} = m_\psi$ for $\psi = d,\ l$. We also fixed $F^{(\psi)} = F_Z = (2.6 \times 10^5\ \text{GeV})^2$ for $\psi = d,\ l$, which corresponds to be the maximal gravitino mass in Eq. (14), $m_{\tilde{G}} = 16$ eV. The D0 limit on Wino mass (195 GeV) is also shown.

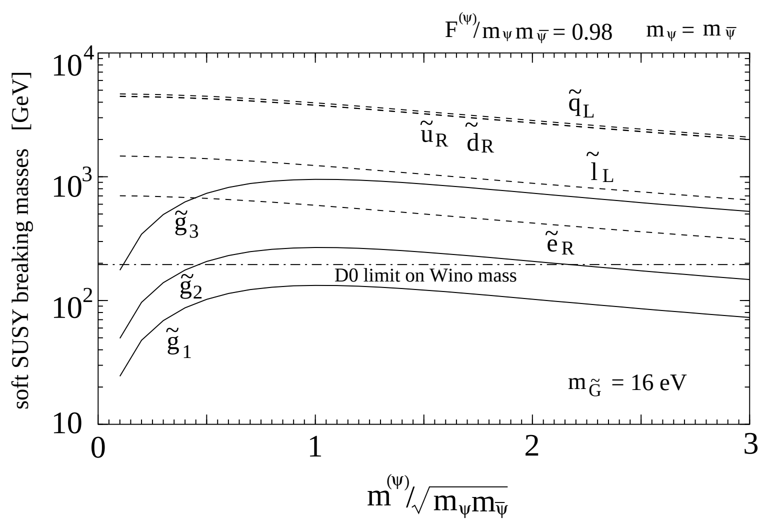

Figure 2: Mass spectrum of the gauginos (solid lines) and sfermions (dashed lines) in the MSSM sector as a function of a parameter $m^{(\psi)}/\sqrt{m_\psi m_{\bar{\psi}}}$ in the next-to-minimal model. Here we have assumed $F^{(\psi)}/(m_\psi m_{\bar{\psi}}) = 0.98$ and $m_{\bar{\psi}} = m_\psi$ for $\psi = d,\ l$, and $m_{\tilde{G}} = 16$ eV. The D0 limit on Wino mass (195 GeV) is also shown.

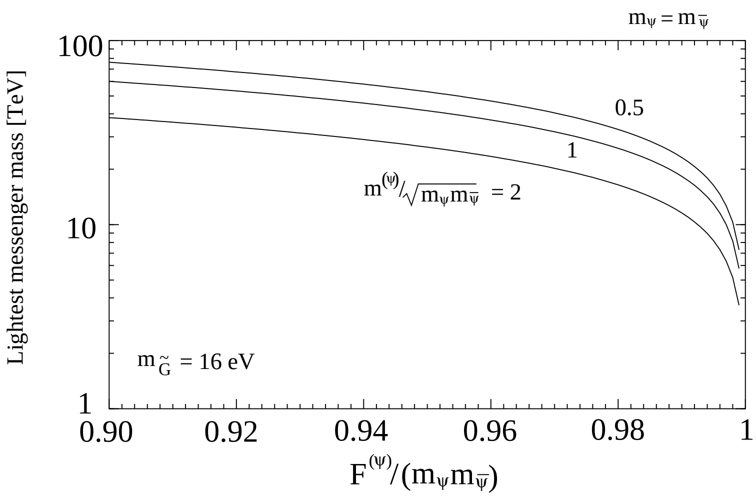

Figure 3: The lightest messenger mass as a function of a parameter $F^\psi/(m_\psi m_{\bar\psi})$. We show lines for $m^{(\psi)}/\sqrt{m_\psi m_{\bar\psi}} = 0.5,\ 1$ and 2. Here we have assumed that $m_\psi = m_{\bar\psi}$ and $m_{\tilde G} = 16$ eV.

$m^{(l)}/\sqrt{m_l m_{\bar l}} \sim 1$. In the region with $F^{(l)}/(m_l m_{\bar l}) \sim 1$ and $m^{(l)}/\sqrt{m_l m_{\bar l}} \sim 1$, one of messenger sleptons gets lighter and it becomes the lightest messenger particle, provided that $F^{(d)}/(m_d m_{\bar d}) < F^{(l)}/(m_l m_{\bar l})$. If $F^{(l)}/(m_l m_{\bar l}) = 1 - \delta$ ($\delta \ll 1$), the lightest messenger slepton mass is approximately given by

$$m_{\tilde\psi_l} \simeq m\sqrt{\frac{\delta}{2}}, \tag{15}$$

which can be calculated by the diagonalization of the mass matrix in Eq. (8). Here we have assumed that all mass parameters are equal to m, $m^{(l)} = m_l = m_{\bar l} \equiv m$. If $\sqrt{F^{(l)}} \leq 2.6 \times 10^5$ GeV (in other words, $m_{\tilde G} \leq 16$ eV) and $F^{(l)}/(m_l m_{\bar l}) \geq 0.93$, the lightest messenger slepton mass should be smaller than about 50 TeV. In Fig. 3, we show a numerical result of the lightest messenger mass as a function of $F^{(\psi)}/(m_\psi m_{\bar\psi})$. Fig. 3 also shows the dependence on $m^{(\psi)}/\sqrt{m_\psi m_{\bar\psi}}$. Here we have assumed $m_{\tilde G} = 16$ eV, and $m_\psi = m_{\bar\psi}$. From Fig. 3, we see the light messenger slepton mass in the range of about $10 - 50$ TeV is predicted in the consistent region of the next-to-minimal model.

The messenger scalar masses within the same $SU(2)$ doublet slepton multiplet are split at tree level by $SU(2)_L \times U(1)_Y$ D-terms. However the tree-level splitting is negligible [19] in the models studied here. The important splitting is generated at one-loop level by gauge boson loops as follows [20]:

$$m_{\tilde\psi_e} - m_{\tilde\psi_\nu} \simeq \frac{1}{2}\alpha m_Z, \tag{16}$$

where $m_{\tilde{\psi}_e}$ ($m_{\tilde{\psi}_\nu}$) is a mass of a charged (neutral) component of the messenger doublet slepton. Therefore the neutral component of the messenger slepton, which we call as the messenger sneutrino, can naturally be the lightest messenger particle, and it can be stable in the model. Interestingly, the stable lightest messenger sneutrino would be a dark matter candidate if its mass is in the range of $10-30$ TeV as pointed out in Refs. [21, 10]. In order to make a viable model for the messenger dark matter, we introduce an extra singlet N and the following additional superpotential [21]: [7]

$$W = \sum_{\psi=d,l} \lambda_\psi N \bar{\psi}_1 \psi_2 + \lambda_H N H_u H_d + \frac{\lambda_N}{3} N^3. \tag{17}$$

The interaction of the singlet N could increase the annihilation cross-section of the messenger sneutrino $\langle \sigma v \rangle$ and it would provide a thermal relic density of the messenger sneutrino $\Omega_{\tilde{\psi}_\nu} h^2$ consistent with the measured dark matter density [21, 10]:

$$\begin{aligned} \Omega_{\tilde{\psi}_\nu} h^2 &\simeq 0.1 \times \left(\frac{10^{-26}\ \mathrm{cm}^3/s}{\langle \sigma v \rangle} \right), \\ \langle \sigma v \rangle &\simeq \frac{y^4 \Lambda^4}{32\pi m_{\tilde{\psi}_\nu}^6} \sim 10^{-26}\ \mathrm{cm}^3/s\ \times \left(\frac{y}{0.4} \right)^4 \left(\frac{\Lambda}{2.6 \times 10^5\ \mathrm{GeV}} \right)^4 \left(\frac{30\ \mathrm{TeV}}{m_{\tilde{\psi}_\nu}} \right)^6, \end{aligned} \tag{18}$$

where y is a function of Yukawa couplings $k_{\psi_a}, \lambda_\psi,\ \lambda_H$ and λ_N, which is of order one.

Furthermore, recently Hooper and March-Russell [10] has proposed that if the mass of messenger sneutrino dark matter is about $20-30$ TeV, it could also account for the multi-TeV gamma-ray spectrum from the galactic center observed by HESS [11, 22]. As can be seen from Fig. 3, the next-to-minimal model can predict such a messenger dark matter if $F^{(l)}/(m_l m_{\bar{l}})$ is about $0.97-0.99$. In this range of parameter space, the predicted Wino mass is about $250-290$ GeV. The gluino (Bino) is also predicted to be lighter than 1 TeV (280 GeV) since $F^{(d)}/(m_d m_{\bar{d}}) < F^{(l)}/(m_l m_{\bar{l}})$ in order for the messenger sneutrino to be lighter than the messenger squarks.[8]

In this paper, we have discussed the direct-transmission model of dynamical SUSY breaking proposed in Ref. [7]. We have found that in order to be consistent with the current cosmological bound on the gravitino mass ($m_{\tilde{G}} < 16$ eV), the direct-transmission of SUSY breaking is required. Combined with the current D0 limit on Wino mass, the minimal model has been ruled out, and the next-to-minimal model is the only consistent model. We have shown that predictions of upper limits on superparticle masses (1.1 TeV, 320 GeV, 160 GeV, 5 TeV, 1.5 TeV and 700 GeV for gluino, Wino,

[7]The superpotential in this model is consistent with R-symmetry, and hence it is natural.

[8]We note that if we assume the unification of mass parameters between messenger quarks and leptons at the GUT scale, we get a relation: $F^{(l)}/(m_l m_{\bar{l}}) \simeq 2F^{(d)}/(m_d m_{\bar{d}})$. However, this relation can be easily changed by the GUT threshold corrections [7]. Also if the messenger quarks and leptons belong to different GUT multiplets, there is no such a unification.

Bino, squarks, left-handed sleptons and right-handed sleptons, respectively). We have also found that in the consistent region, the next-to-minimal model predicts the light messenger slepton in the mass range of $10 - 50$ TeV, and hence it would be an interesting dark matter candidate to account for the multi-TeV gamma-ray spectrum observed by HESS experiment. Therefore, not only current and future sparticle searches but also more multi-TeV gamma-ray data from HESS and Cangaroo III in the coming years would provide a further important insight for the direct-transmission model of the dynamical SUSY breaking.

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